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16. ABSTRACT This paper discusses presentations made during a symposium on novel concepts, methods, and advanced technology in particulate/gas separation. The symposium, held at the University of Notre Dame and sponsored by the National Science Foundation and the Environmental Protection Agency, was held both to identify new research areas and to stimulate future research activities. The presentations included two general lectures by internationally known scientists (Dr. M.Benarie of France and Professor F. Loffler of West Germany) and 17 invited lectures by other prominent experts. New concepts and methods include the use of acoustics, high gradient magnetic fields, and electrostatic filtration in patriculate/gas separation.

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NOVEL CONCEPTS, METHODS AND ADVANCED TECHNOLOGY IN PARTICULATE/GAS SEPARATION

Report on a Workshop

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Particulate/gas separation techniques have been the subject of much research in recent years. From this research have come new concepts and methods, such as the use of acoustics, high gradient magnetic fields, and electrostatic filtration in particulate/gas separation. Some of the results of the work in the field were discussed by scientists in a workshop held at the University of Notre Dame in April 1977. The highlights of the discussions at that workshop are presented here.

Recently there has been a substantial growth in research dealing with new concepts and methods in particulate/gas separation, such as electrostatic filtration, high gradient magnetic separation, and the utilization of acoustics in particulate/gas separation. In order to stimulate further research activities in these areas, a workshop entitled, "Novel Concepts, Methods, and Advanced Technology in Particulate/Gas Separation," was organized with the support of the National Science Foundation and Environmental Protection Agency. The workshop took place April 20-22, 1977, at the University of Notre Dame.

Three groups of experts were invited to contribute to the workshop: theoretical analysts, experimentalists, and design and application specialists. The interaction among these groups through presentations and discussions was particularly emphasized. Seventeen invited lectures by prominent experts and two general lectures by two internationally known scientists, were presented. Each lecture was followed by a designated discusser whose prepared discussion was followed by a general discussion. A panel session on "New Directions in Particulate/Gas Separation Research" was also held. All workshop sessions were recorded and all presentations, discussions, and the panel session are included in the recently published proceedings.[1] A concise summary of the workshop follows.

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Acoustics in Particulate/Gas Separation

David S. Scott of the University of Toronto lectured on the status of pulse-jet acoustic dust conditioning and some new potential applications. Acoustic conditioning of fine-particle aerosols increases the mean size and decreases the number density of particles through exposure to finite-amplitude acoustic fields. This important change in particulate size distribution allows an increase in the collection efficiency of a downstream dust collector and/or a reduction in the overall particulate separation cost. Scott noted that although the principle of acoustic dust conditioning (ADC) has been known for some time and has been shown to be technically effective, the process has had little industrial application. Scott felt that this is primarily a consequence of high operating costs due to specific power requirements and capital investment.

However, with the utilization of a new technique in sound generation, the proposed combination of ADC with wet scrubbers or mechanical collectors appears to open up an exciting new potential and feasible application for the use of acoustics in fine particulate control. Two recent developments are the studies for the possible utilization of ADC/wet scrubbers in the pulp and paper industry and ADC/mechanical separation in high-pressure/temperature fluidized-bed coal combustors.

A study on acoustic and turbulent agglomeration of sodium-fire aerosols was reported by *William C. Hinds, et al.*

of Harvard University. The aim was to examine the feasibility of using direct application air cleaning as a treatment method for high concentrations of sodium-fire aerosols that would likely fill a reactor containment vessel following a release inside a liquid metal fast-breeder reactor. Tests of turbulent and acoustic agglomeration of captive sodium-fire aerosols at concentrations of 0.1 to 20 g/m^3 were conducted in 90 m^3 and 0.65 $in.^3$ vessels to evaluate these mechanisms for direct application air cleaning systems.

It was noted that turbulent motion and high intensity reverberant acoustic fields induce rapid agglomeration of sodium-fire aerosols. The higher the initial mass concentration, the more effective are the agglomeration mechanisms that produce enhanced sedimentation. For the same energy expenditure, turbulence appears to be a more effective agglomerating mechanism than acoustic energy at a fixed mass concentration. Moreover, because of the relative ease of generating turbulence vs. generating a large scale high intensity sound field, turbulent agglomeration was preferred.

James A. Gieseke of Battelle's Columbus Laboratories compared Battelle's analytical results (based on the HAARM-2 code) and the experimental results reported by Hinds, *et al.* Particularly for low turbulence level, agreement appeared to be very good.

David T. Shaw of the State University of New York at Buffalo reported on new applications of acoustic agglomerators in particulate emission control. Shaw stated that sonic agglomerators have some characteristics which make them uniquely suitable for certain special applications. These include the acoustic conditioning of fine particulate emissions (particle diameter between 0.2 and 2 μm); the suppression of radioactive sodium-fire aerosol due to hypothetical accidents in liquid metal fast-breeder reactors; and the control of particulate emission under special conditions where conventional equipment and techniques are not applicable. Shaw's objectives were to describe these new acoustic applications and to identify the predominant sonic agglomeration mechanism for each application. He noted that acoustic agglomeration should only be used for the effective control of fine particles (diameters between 0.02 and 2 μm) for which conventional devices are not effective. For such applications a relatively high frequency acoustic field must be used so that only fine particles oscillate while particles with diameters larger than 2 μm are relatively stationary. Thus, with only the oscillation of fine particles consuming acoustic energy, power consumption for the production of the acoustic field can be significantly reduced.

William M. Swift of the Argonne National Laboratory (ANL) described a research program for the investigation of the effect of acoustic dust conditioning on the efficiency of particulate removal devices in the flue gas system of ANL's experimental fluidized-bed combustor. He also emphasized that the agglomeration mechanisms considered by Shaw (i.e., orthokinetic vibration and hydrodynamic interaction) are but two of nine mechanisms known to have some effect on agglomeration kinetics. Shaw replied that the other seven are mostly associated with turbulence and cannot be identified in his research program.

Paul D. Scholz of the University of Iowa reported on an experimental project to investigate the effects of an ac electric field and a traveling-wave sound field on the collision rates between suspended particles with radii less than about 0.3 μm. A brief discussion of the theoretical collision rates in the free molecule regime was also included for the cases where each field was applied separately. Velocity profiles and values of the turbulent intensity in the continuous flow coagulation tube were presented and discussed. Scholz concluded that his simple kinetic model, based on a dilute model of hard sphere particles suspended in a gas, seemed to be qualitatively correct.

Andrew R. McFarland of Texas A&M University commented on an experimental program investigating the capability of an electrostatic aerosol analyzer. He stated that a substantial augmentation appeared to be needed.

High Gradient Magnetic Field in Particulate/Gas Separation

Engineering aspects of batch-type and continuously operating magnetic particulate/gas separation methods were compared by *Robin R. Oder*, now of Gulf Research and Development Co. The comparison was made in conceptual applications to desulfurization of dry, finely pulverized, pretreated coal. With pretreatment, it was claimed that magnetic separability of mineral sulfur forms occurring in coal could be considerably enhanced so that a variety of magnetic methods could be expected to be applicable. According to Oder, in processing finely pulverized coal, batch-operated High Gradient Magnetic Separation (HGMS) offers the advantage of efficient desulfurization of high coal-value recovery but can incur practical difficulties associated with packed-bed operation. By contrast, continuously operating smooth bore magnetic separators have the advantages and simplicity of continuous operation but are not as effective in desulfurization in high gas-velocity applications. Tradeoffs between separation performance and total process requirements will be very important in future developments of magnetic methods for particulate/gas separation.

Technical and cost comparisons for HGMS and quadrupole magnetic separation indicates that the HGMS installation is estimated to be about a factor of 5 less expensive than the bank of 33 quadrupoles and consumes about one-seventh the power. If auxiliary fan requirements are included, however, the HGMS installation cost estimate increases to about one-fourth that of the quadrupole, and the total power consumption estimate increases to about one-half that of the quadrupole installation. Including fan requirements, operating costs estimated for the HGMS installation are only about one-half those of the conventional iron-return-electromagnet quadrupole structure.

E. Maxwell of Massachusetts Institute of Technology stressed that there are really no experimental data at this time to support the implicit assumption that the velocity air streams will be as straightforward as the separation from water slurries. Based on his work, Maxwell stated that coal which can be successfully processed in water slurries by HGMS does not respond when simply propelled through a matrix in a high air stream. Agglomeration and stickiness appear to be major problems. It may be that pretreatment of the coal to enhance the magnetic susceptibility of the pyrite may help overcome this difficulty; but this has yet to be established.

It appears that in the last decade research and commercial applications have demonstrated that high gradient magnetic separation (HGMS) is an effective and economical method of removing small paramagnetic particles from selected liquid streams. A presentation by EPA's *Dennis C. Drehmel* and *Charles H. Gooding* of the Research Triangle Institute utilized theoretical and experimental investigations on HGMS to evaluate the potential success of the process in removing fine paramagnetic particles from gas streams. Industrial sources of fine paramagnetic particles were identified, and the steelmaking basic oxygen furnace (BOF) was selected as the primary candidate for initial HGMS evaluation. A bench scale apparatus was constructed and the HGMS experiments were conducted using redispersed BOF dust. With existing theoretical equations as a guideline, the experimental data were analyzed and favorable operating conditions were identified.

Basically the objective of Drehmel and Gooding's work was to demonstrate on a small scale that HGMS may be an effective and economical technique for the control of fine particle emissions from selected industrial sources. The following conclusions were drawn from their work:

1. Fundamental theory predicts the potential success of the concept.
2. Preliminary experiments support the potential capability of at least 90% removal of all submicron particulate from BOF furnaces. Collection of submicron particulate might actually be enhanced by low magnetic fields.
3. No inherent health and safety hazards or any other unfavorable environmental impacts have been associated with HGMS application,
4. No prohibitive design or reliability problems have been identified.
5. HGMS is potentially applicable to several sources of fine particulate; retrofit capability should be enhanced by high gas velocities demonstrated in preliminary experiments.

R. Duncan Hay of Magnetic Engineering Associates indicated that since HGMS is based on intrinsic magnetic susceptibility, its application must be limited to materials that have magnetic properties. On a practical level the separation of fine particulates in a large volume gas stream may only be possible with materials of high magnetic susceptibility.

Research needs and opportunities in high gradient magnetic separation of particulate/gas systems were discussed by *Y. A. Liu* and *C. J. Lin* of Auburn University. Their discussion was divided into three categories.

1. Process and engineering research oriented toward application of existing devices.
2. Fundamental research aimed at developing a better understanding of the mechanisms and principles of the separation.
3. Scientific and engineering development of new separation methods and devices.

Liu noted that HGMS is also applicable to the separation of nonmagnetic materials which can be made to associate with magnetic seeding materials.

David R. Kelland of Massachusetts Institute of Technology pointed out that a careful distinction is necessary between particulate/gas systems; in this case, dry coal cleaning and water slurry separation. For a given coal in which the inorganic matter has been liberated by grinding or other means, most of the inorganic sulfur minerals can be removed by HGMS along with some of the ash-forming mineral matter. The same cannot be said yet for dry separation when a number of technical problems remain. It is not clear what kind of, or how much, pretreatment might be necessary, or how the HGMS process might be applied.

F. J. Friedlander of Purdue University reviewed single-wire models in HGMS. His main concern was with the collection process on single fibers which can be considered the basic "building block" of the more complicated systems in actual use. The fibers serve both as collection centers and as means of producing the high gradient field. They have to have appropriate mechanical and chemical properties (e.g., they should not be corroded by water, usually used as the fluid that carries particles). Secondly, they should be ferromagnetic with a large magnetic moment so that high gradients can be achieved. The shape of the fiber cross-section is another factor that determines the magnitude of the gradient: small diameter wires or steel fibers with relatively sharp edges are used to obtain large gradients. Friedlander presented detailed experimental results of particle building on single collecting fibers (nickel wire) for several arrangements of the fiber relative to the flow and the applied magnetic field.

William F. Lawson, Jr. of the U. S. Department of Energy's Morgantown Energy Research Center pointed out that the agreement between gross filter efficiencies calculated using Watson's theory and results of actual filter experiments is generally unsatisfactory.

Only the slower flows substantiate the theoretical predictions in which particle inertia and gravitational forces are disregarded. Different flow fields around the cylindrical fiber have been used in single fiber theories and have yielded quite different quantitative results. Moreover the two factors which make inertial effects manifest in dry HGMS are the reduced viscosity of the medium and the typically higher flow velocities used in gas filtration. The reduced fluid mass density can cause the gravitational pull to be more significant than with denser liquids.

Teoman Ariman of the University of Notre Dame cautioned that some of his work on multiple fiber filter theory indicates that the effect of neighboring fibers in large arrays can be quite significant. The multiple fiber model indicates that single fiber models overestimate the collection efficiency. Furthermore, when porosity of the filter increases, there is a decrease in the collection efficiency which is in agreement with the recent experimental work by Iinoya of Japan.[1]

Electrostatic Filtration

A general lecture entitled, "The Influence of Electrostatic Forces and of the Probability of Adhesion for Particle Collection in Fibrous Filters," was presented by *Friedrich Löffler* of the University of Karlsruhe, West Germany. He stated that, although a number of publications are available on fibrous filters which have long been used industrially to separate solid or liquid particles from gases, some questions still remain unanswered. According to Löffler, striking differences between theoretical calculations and experiments have been observed in some cases where the particle size range is above 0.5-1μm and the Reynold's number is larger than 0.5. One important reason for these differences is that the significance of the probability of adhesion has been neglected; i.e., it has been generally assumed that all particles striking a fiber would also stick there. However, this is frequently not so. In order to elucidate some of the open questions on transport and adhesion processes, a three-part research program has been carried out: theoretical and experimental studies of single fibers, model fibers consisting of parallel fibers, and industrial filters. Some of the theoretical and experimental results were discussed in detail. The enormous influence of electrostatic forces was demonstrated, especially for smaller particles. It was also noted that so far no final description of the probability of adhesions is possible.

H. C. Yeh of Lovelace Biomedical and Environmental Research Institute of Albuquerque indicated that, in the case of charged particles with fibers either charged or uncharged, the electrostatic force changes with time as charged particles continue to be collected on the fiber. The effects of these changes are undetermined. Yeh also stated that the coefficient of adhesion is important not only in high velocity filtration, but also in sampling and/or sizing devices such as impactors.

James R. Melcher of the Massachusetts Institute of Technology reviewed electrofluidized beds for industrial scale air pollution control. He noted that an electrofluidized bed (EFB) is a shallow bed of particles, fluidized by the polluted gas, with an electric field applied by electrodes. Typically, the gas-entrained pollutant particles are electri-

cally charged by ion impact prior to entering the EFB. Stressed as they are by the electric field, the bed particles act as collection sites for pollutants. A major incentive for using the EFB is the extremely short gas residence time required for collection of submicron particulate.

Melcher provided an overview of the fundamental and practical development of the EFB, beginning with its application to the control of submicron particulates. Models and corroborating experiments establish fundamental particle collection coefficients, extend two-phase fluidized-bed theory to account for bubble bypassing, and describe the performance with ac excitation. Practical developments in the control of oil ash and asphaltic fume were described. Savings from a reduced need for power conditioning equipment are an obvious advantage of being able to use ac voltages to excite the EFB. But, perhaps a more important motive comes from the difficulty encountered when conventional ESP's with dc energization are used to collect highly resistive materials such as fly ash while the EFB appeared to be more successful.

Robert B. Reif of Battelle's Columbus Laboratories made a presentation on an electroinertial air cleaner. Inertial air cleaners (consisting of a bank of straight-flow tubes, each tube having a swirl means to cause dust to be centrifugally thrown outward toward the tube wall) are well known for engine air cleaning operation. For particles smaller than 5 μm, an electrostatic separator action was added through a fine wire at a potential of approximately 15–20 kV extended through the tube centerline with the tube wall at ground potential to establish a flow of negative ions. Better collection efficiency is expected.

A new approach to calculating approximate single-collector collection efficiencies was presented by *Douglas W. Cooper* of Harvard University. This approach eliminates the need to calculate particle trajectories for particles of negligible inertia. Cooper's approach emphasizes the significance of aerosol concentration profile. It shows that increased collection efficiency results from improved mixing of the aerosol in the vicinity of the collectors, perhaps through induced turbulence. The aim of his work is to make it easier to calculate approximate collection efficiencies of control devices (such as scrubbers and filters) which employ electrostatics to augment their usual collection mechanisms and to clarify the role of electrostatics in such devices.

Kenneth A. Nielsen of Union Carbide Corporation stated that the particle flux method used by Cooper can only be applied to solenoidal particle fields resulting from incompressible flows and solenoidal forces. Such forces include the gravitational force and coulombic and external electric field forces on a charged particle.

Dennis J. Helfritch of American Precision Industries and *Teoman Ariman* made a presentation on electrostatic filtration—design and field performance. The results of recent bench scale tests in an electrostatic field were used to illustrate the variation of pressure drop with particle charge. Dust particles were charged prior to deposition by means of passage through a corona discharge. The results clearly indicated that there was a dramatic decrease in the pressure drop with the increased electrostatic charge on particles. Although there were qualitative differences in the magnitude of the decrease, the effect of the electrostatic charge was qualitatively identical for all dust samples tested. Fabric type also exerts some influence on the electrostatic filtration process, but the relative differences among fabrics are small.

A new industrial fabric filter (Apitron) utilizing electrostatics was described and its performance was demonstrated on several typical applications. Two basic conclusions were drawn from the field tests. Apitron yields improved collection efficiency particularly for fine particulates and has substantially reduced space requirements due to the decrease in the pressure drop. It was further noted that the decrease was due to the formation of a much more porous dust cake in electrostatic filtration.

Further studies on saturation point, the charge on particles, the effect of relative humidity on pressure drop, and economics of the electrostatic fabric filtration were suggested by *T. M. Kuzay* of Argonne National Laboratory.

Richard R. Koppang of TRW Inc. reported on TRW's Charged Droplet Scrubber (CDS) which combines high energy wet scrubbing collection for micron size particulate with electrostatic precipitation for submicron particulate collection. The gas cleaning process steps of water droplet atomization, acceleration, particulate collection, and demisting are performed through applied principles of electrostatics within a gas treatment equipment length of 8 feet. Other CDS operating advantages include: no moving parts in the gas stream, low sensitivity to particulate physical properties, and low liquid-to-gas ratios.

A comparison was provided by *Michael J. Pilat* of the University of Washington between TRW's CDS system and the University of Washington's electrostatic scrubber (UWES). In the UWES, particles are electrostatically charged (negative polarity) in the corona section. The gases and charged particles flow into a scrubber chamber into which electrostatically charged water droplets (positive polarity) are sprayed to collect charged particles.

Albert Baril, Jr. of the U.S. Department of Agriculture made a presentation on the research on new equipment for dust collection. He cited a wet wall electroinertial unit, a high speed rotary drum air cleaner and a fluid electrode precipitator as examples of innovative designs and applications. *Dennis J. Helfritch* discussed the collection efficiency and energy requirement aspects of these devices.

"Dielectrophoretic Air Filtration: Progress and Problem" was presented by *George H. Fielding* of the U.S. Naval Research Laboratory. Dielectrophoretic air filters under development at the Naval Research Laboratory, as well as those previously reported or currently manufactured, were discussed with a view to establishing successful design principles.

Edward R. Frederick of the Air Pollution Control Association discussed the same subject. He noted that, since particulates and fabric of high resistivity cannot be charged, except naturally, it was quite possible that some inconsistencies in performance and nonreproducibility of results indicated with the various dielectrophoretic devices reported by Fielding, *et al.* could be attributed to such variations.

The collection of fine particulates using a foam scrubber was described by *Tom E. Ctvrtnicek* of Monsonto Research Corporation. Fundamental principles for the two primary collection mechanisms, diffusion and sedimentation, were discussed. These principles were experimentally verified for particles between 0.18 and 1.0 μm diameter on a bench (2.5 acfm) and small pilot scale (500 acfm). Comparison of economics indicates that the foam scrubber can be competitive with conventional collection devices.

George E. Lamb of the Textile Research Institute questioned the low collection efficiency for the technique utilized in the foam scrubber. He provided an estimate for the bubble size required to achieve an acceptable collection efficiency.

The anomalous behavior of asbestos

fibers was described by *James W. Gentry* of the University of Maryland. He indicated that there has been evidence of a link between cancer and asbestos fibers. The aerodynamic diameter and dynamic shape factors were defined for a nonspherical particle and, in particular, for asbestos fibers.

Michel M. Benarie of the National Institute for Applied Chemistry, Paris, France, discussed high temperature filtration. Adding temperature as a variable to the classic test parameters (particle size and force velocity) demonstrated that the flow field in fibrous filters, even at low fiber Reynold's number, shows departures from laminarity. Two phenomena might be involved: unsteady flow at capillary entrances and branchings, and secondary flow. The turbulence-like phenomena improve the filter performance in the sense of lowering pressure drop and increasing efficiency.

K. T. Yang of the University of Notre Dame noted that more studies, either analytical or empirical, are needed to provide a better predictive theory for low temperature filtration before any meaningful predictions can be made at elevated temperature.

The last part of the workshop was devoted to a panel discussion entitled "New Directions in Particulate/Gas Separation Research." The session was moderated by *Benjamin Y. H. Liu* of the University of Minnesota. *Teoman Ariman, Michel M. Benarie, Dennis C. Drehmel, Robin R. Oder and David S. Scott* were members of the panel. Formal presentations by the moderator and panel members were followed by a lively discussion with the contributions from workshop participants. A complete description of this very stimulating panel session, as well as all the invited and general papers, and written and oral discussions in their entireties were included in the proceedings of the workshop.[1]

Reference

1. *Novel Concepts, Methods and Advanced Technology in Particulate-Gas Separation*, Edited by Teoman Ariman, Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, IN 46556, 1979, 458 pp. Also EPA-600/7-78-170, August 1978.

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